R-99-10

REPAIRING CONCRETE WITH SHOTCRETE
(A Primer for Bureau of Reclamation Staff)

November 1999

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation

Technical Service Center
Civil Engineering Services
Materials Engineering and Research Laboratory
Denver, Colorado

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
November 1999

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE

Repairing Concrete with Shotcrete (A Primer for Bureau of Reclamation Staff)

5. FUNDING NUMBERS

6. AUTHOR(S)

Todd Rutenbeck

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Bureau of Reclamation
Technical Service Center
Civil Engineering Services
Materials Engineering and Research Laboratory
Denver, Colorado

8. PERFORMING ORGANIZATION REPORT NUMBER

R-99-10

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Same

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Shotcrete is mortar or concrete pneumatically projected at high velocity onto a surface. Shotcrete has been used in the repair of concrete for almost 90 years. There have been many successful repairs, and there have been failures. The purpose of this report is to serve as an introduction to the subject for Bureau of Reclamation (Reclamation) staff considering use of shotcrete for concrete repair. This report does not discuss Reclamation shotcrete projects, but discusses what has been done outside Reclamation over the past 10 years and informs Reclamation staff of current practice in the industry. This report describes the wet-mix and dry-mix shotcrete processes and the advantages of each. It describes the similarities of shotcrete to conventionally placed concrete and the differences between the two. The specific application of shotcrete technology to concrete repair is discussed. Brief summaries of a variety of projects appearing in the literature over the past 10 years are given, and other topics from the literature are listed. These projects illustrate current shotcrete technology and its versatility for concrete repair. Reclamation can continue to successfully use shotcrete as one of its methods of concrete repair if current technology is understood and shotcrete is used within its limitations.

14. SUBJECT TERMS

concrete repair, shotcrete, wet-mix, dry-mix, thin repairs, reinforcement, prestressing, silica fume, concrete dams, bridges, sculpture, remote-controlled nozzle.

15. NUMBER OF PAGES
14

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UL	UL	UL	UL

R-99-10

REPAIRING CONCRETE WITH SHOTCRETE (A Primer for Bureau of Reclamation Staff)

by

Todd Rutenbeck

Technical Service Center
Civil Engineering Services
Materials Engineering and Research Laboratory
Denver, Colorado

November 1999

UNITED STATES DEPARTMENT OF THE INTERIOR ′ BUREAU OF RECLAMATION

Mission Statements

U.S. Department of the Interior

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to tribes.

Bureau of Reclamation

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

CONTENTS

INTRODUCTION AND EXECUTIVE SUMMARY

Shotcrete is mortar or concrete pneumatically projected at high velocity onto a surface. [1] Shotcrete has been used in the repair of concrete for almost 90 years. There have been many successful repairs, and there have been failures. The purpose of this report is to serve as an introduction to the subject for Bureau of Reclamation (Reclamation) staff considering use of shotcrete for concrete repair. This report does not discuss Reclamation shotcrete projects, but discusses what has been done outside Reclamation over the past 10 years and informs Reclamation staff of current practice in the industry. This report describes the wet-mix and dry-mix shotcrete processes and the advantages of each. It describes the similarities of shotcrete to conventionally placed concrete and the differences between the two. The specific application of shotcrete technology to concrete repair is discussed. Brief summaries of a variety of projects appearing in the literature over the past 10 years are given, and other topics from the literature are listed. These projects illustrate current shotcrete technology and its versatility for concrete repair. Reclamation can continue to successfully use shotcrete as one of its methods of concrete repair if current technology is understood and shotcrete is used within its limitations.

WHAT SHOTCRETE IS AND IS NOT

Shotcreting is a method of placing concrete or mortar. While shotcrete is, in some respects, unique; it is neither inherently superior to nor inherently inferior to conventionally placed concrete or mortar. Many articles on shotcrete begin with the American Concrete Institute (ACI) definition: shotcrete is mortar or concrete pneumatically projected at high velocity onto a surface. [1] There are two processes for applying shotcrete. ACI defines dry-mix shotcrete as shotcrete in which most of the mixing water is added at the nozzle; and wet-mix shotcrete as shotcrete in which the ingredients, including water, are mixed before introduction into the delivery hose; accelerator, if used, is normally added at the nozzle. [1]

Based on these definitions, shotcrete can be either mortar (containing sand for aggregate) or concrete (containing sand and coarse aggregate) and can be applied by either the dry-mix or the wet-mix process. There are numerous other terms and brand names that have been used over the years for shotcrete. One of the most commonly used terms is Gunite, actually a brand name, that is frequently used to mean shotcrete mortar applied by the dry-mix process. This report will use the above American Concrete Institute definitions for shotcrete. Other available ACI documents on shotcrete include 506R-95, Guide to Shotcrete; 506.1R-84, State of the Art Report on Fiber Reinforced Shotcrete; 506.2-95, Specification for Shotcrete; 506.3R-91, Guide to Certification of Shotcrete Nozzlemen; 506.4R-94, Guide for the Evaluation of Shotcrete; and C-18, Shotcrete.

In dry-mix shotcreting, cement and damp aggregate are mixed. (The aggregate is dampened with about 5 percent water by weight of aggregate to reduce dust.) This dry-mix material is then fed into the shotcrete machine or gun. The gun feeds the material into a hose where the material is transported by compressed air to a nozzle. The nozzle contains a water ring that injects water into the material stream just before it exits and travels to the application surface at high velocity (about 500 feet/second). A water valve allows the nozzleman to control water content. Final mixing occurs as the materials hit the application surface, and the nozzle is usually moved in a circular pattern to assist in mixing. Set-accelerating admixtures, frequently used in tunnel support shotcrete, can be added as a powder as the mixture enters the gun, or can be added as a liquid in the water supply. Other materials can be added in a similar manner or can be mixed with the dry material, depending on the type of material being added.

In wet-mix shotcrete, all ingredients except accelerators are mixed to form a concrete or mortar. No water is added at the nozzle. The concrete or mortar then enters the gun that forces the mixture through the delivery hose to the nozzle, where compressed air is used to increase the velocity of the stream and improve the gunning pattern. Accelerators can be added at the nozzle. Many wet-mix guns are essentially concrete pumps of the proper capacity for shotcreting.

Advantages of the dry-mix process include an excellent bond to existing materials, longer hose lengths, dry material can be easier to remove from plugged hoses than wet concrete, water content can be instantly adjusted to meet field conditions, set accelerators are easier to add, and equipment is usually cheaper to buy and maintain.

Advantages of the wet-mix process include large capacity guns, less rebound due to complete mixing, less dust, more uniform in-place material, more accurate control of water content, and better success in adding air-entraining admixtures.

Because shotcreting is a method for placing mortar or concrete, shotcrete has many similarities to conventionally placed mortar or concrete. Shotcrete can use water-reducing, air-entraining, and set-accelerating admixtures, as well as other admixtures. Shotcrete can contain pozzolan, silica fume, fibers, and a wide range of cement types. Shotcreting can be used to place polymer concrete. Shotcrete can be finished and cured in a manner similar to conventional concrete. It can be applied around congested reinforcement, and it can be used in prestressed construction.

However, because shotcreting is a unique method of placing concrete or mortar, it has some characteristics not found in conventionally placed materials. Shotcrete requires a minimum of formwork, as it will stay in place on vertical and on overhead surfaces. While bonding agents are sometimes used to make shotcrete adhere to old concrete (especially if good curing is in question), such precautions are usually not necessary. This is, in part, due to the fact that the shotcreting process ensures that a cement-rich mortar layer forms on the old surface as the shotcrete is applied. Larger sand and gravel particles bounce off the application surface until a cushion of mortar thick enough to receive them is in place. The skill of the nozzleman is critical to obtaining high quality shotcrete. This is both an advantage and a disadvantage for shotcrete. A highly skilled nozzleman can use shotcrete’s flexibility to create unusual and difficult shapes. With the dry-process, the nozzleman can adjust water content to meet job conditions. An inexperienced nozzleman, however, can lower the quality of shotcrete by burying rebound and overspray in the work, and by increasing (or decreasing) water content enough to significantly lower shotcrete strengths. Improper nozzle technique can cause porous and variable quality shotcrete and can cause incomplete filling around reinforcing bars. Many jobs with either dry-mix or wet-mix shotcrete require a blowpipe operator using compressed air to work ahead of the nozzleman to remove rebound that otherwise could be buried in the shotcrete placement. Shotcrete usually has a higher cement content than conventionally placed concrete, and usually has a maximum coarse aggregate size of 3/4 inch or less. Shotcrete with a maximum aggregate size of 3/8 inch is commonly used as is shotcrete with sand only.

Shotcrete has been used in many ways during its 90-year history. It has been used to line canals and swimming pools, construct buildings, and make retaining walls. It has been used for rock slope stability and protective coatings. Shotcrete has been used for refractory linings. It has been used to make unusually shaped structures. Dome-shaped buildings have been constructed by applying shotcrete over a mound of earth that is later removed, or by applying shotcrete to inflatable and other unique forms. Shotcrete has been used to support tunnels during construction and as final support and lining. When applied in tunnel construction immediately after blasting, a thin layer of shotcrete can stabilize newly exposed rock; and the composite arch of rock and shotcrete becomes load-supporting. Shotcrete has been used throughout the twentieth century for repairing concrete structures, the subject of this report.

SHOTCRETE TECHNOLOGY FOR CONCRETE REPAIR

Both dry-mix and wet-mix shotcrete are used in concrete repair work, but the use of dry-mix shotcrete is more common. This is due, in part, to a tradition of successful use for repairs (dry-mix shotcrete has been used for about 90 years, while wet-mix shotcrete has been in use about half that long); but is also due to the fact that many repair jobs involve small quantities of shotcrete, and most wet-mix guns are designed for high production.

There are individuals who view shotcrete as a vastly superior repair material that, due to its unique qualities, always has excellent bond and durability. There are others who, having seen thin shotcrete repairs fail, conclude that shotcrete is an inferior repair material with no long-term durability. The truth lies somewhere between these two extreme views.

While shotcrete can make a well-bonded, dense, and durable repair, it cannot repeal the laws of physics. Thin repairs, whether shotcrete or conventional concrete, are normally inherently less durable than thicker, more massive repairs. Even durable, well-bonded repair materials can be prone to failure when used in thin applications. Differences from the old concrete in coefficient of thermal expansion, modulus of elasticity, permeability, and other properties can lead to failure. Shotcrete, especially dry-mix, has often been used successfully in thin repairs where it is applied in dense, well-bonded layers; but it has been criticized in applications where thin repairs fail. The fact remains that conventional mortar or concrete would also have failed in these repairs if applied in the same thin layers. The overall design and application of a repair must be well-planned to produce durability. Shotcrete has inherent advantages in making thin repairs, but total thickness, finishing, curing, material properties, and anchoring with reinforcement as well as corrosion of existing reinforcement must be evaluated in making a repair durable.

Silica fume, a by-product of electric arc furnaces that produce elemental silicon or ferro-silicon alloys, can improve several shotcrete properties in concrete repairs. Silica fume is a fine pozzolanic material with a particle size about 1/100 the size of a particle of portland cement. It can be used to replace a small percentage (usually less than 15 percent) of portland cement in a concrete or shotcrete mixture. Shotcrete made with silica fume can have greater bond strength, higher durability, lower permeability, and higher strength than conventional shotcrete. Silica fume in shotcrete can also improve shotcrete placement by giving greater adhesion to the application surface and allowing thicker layers of shotcrete to be applied without the use of set-accelerating admixtures. Wolsiefer and Morgan [2] reported that much greater thicknesses could be shot overhead when using silica fume in wet-mix shotcrete; but very little difference in rebound amounts was noted since wet-mix shotcrete has little rebound. Silica fume in dry-mix shotcrete also allowed large thicknesses when shooting overhead and had the additional benefit of about a 50 percent reduction in rebound, thus reducing the overall cost of the application. Wolsiefer and Morgan obtained modest increases in both compressive and flexural strength of dry-mix shotcrete and substantial increases in wet-mix shotcrete when using silica fume. While silica fume is a very fine-grained material and can increase needed water contents, Wolsiefer and Morgan found that by using a superplasticizer in wet-mix shotcrete containing silica fume, water content and drying shrinkage were held to equal or less than that for conventional shotcrete. For dry-mix shotcrete, water demand varied little with the addition of silica fume, and thus drying shrinkage was about the same for shotcrete with or without silica fume.

While silica fume increases the cost of shotcrete materials, its use may have little effect on the overall project cost. Lower rebound (for dry-mix) and faster production due to thicker layers of application could reduce overall costs, and in many repair jobs the volume of shotcrete is small, and thus, materials costs are a small percentage of overall project cost. On some repair projects, fibers are added to silica fume or conventional shotcrete to further enhance physical properties of the shotcrete.

An article by James Warner [3] discusses shotcrete use for repair and rehabilitation. Shotcreting equipment and techniques vary depending on the size and complexity of the repair project. Spalls and small repair areas are usually thin and contain little or no reinforcing. The dry-mix process is preferred for such applications, as a small gun with a low production rate is needed. Such defects can be filled using a small circular pattern with the nozzle to fill the spall and to ensure a uniform dry-mix product. Finishing is easily accomplished using the surrounding concrete for alignment. Warner also discusses thin repair sections with limited reinforcing. Such repairs are usually less than 6 inches deep and can usually be placed in a single pass. The ½-inch or smaller bars or the wire mesh are easy to completely encapsulate with either the wet-mix or the dry-mix process, because the shotcrete flows around the reinforcement when the nozzle is held in its usual position perpendicular to the repair surface. Wet-mix can be faster and more economical if large volumes of shotcrete are involved.   In thick, heavily-reinforced sections, shotcrete has the advantages of speed of application and of requiring minimal forming. In California, such applications are frequently used in the seismic strengthening of existing structures. Great skill and proper reinforcement design are needed to produce quality work. Full-scale mock-ups of the work are often required to prove the contractor’s abilities. Special nozzle techniques are needed to prevent inclusion of rebound and to completely encapsulate the reinforcing bars. The high cement content of most shotcrete, combined with high velocity impact, gives good compaction. The high cement content also assists in obtaining high strengths. [3]   Reinforcing bars up to No. 14, with spacing as small as 3 inches, have been successfully encased with shotcrete. Multiple layers of No. 6 bars spaced at 6 inches on center have also been used successfully in rehabilitation projects using shotcrete. [4] Shotcrete for seismic strengthening work had its start in California when the Field Act legislation was passed in response to the 1933 Long Beach earthquake. The Field Act required strengthening of all hospital and school buildings to a prescribed level. Reinforced dry-mix shotcrete was used to strengthen walls in many unreinforced masonry schools and hospitals. As this method developed, thicker and more heavily reinforced sections became more common. In more recent years, development and use of the wet-mix process showed advantages in large volume placements containing heavy reinforcement. Wet-mix shotcrete has little rebound, and usually produces a more uniform in-place material. It also requires less skill to successfully encapsulate reinforcement.[4] Forms for structural sections need to be designed to not interfere with nozzle movement and direction. In some cases, formwork needs to be erected in sections as the work progresses to allow nozzle access and complete filling with quality shotcrete.[4]

It is apparent that shotcrete technology has advantages in many concrete repair projects. The minimum amount of formwork required, the ability to bond to existing surfaces, the ability to stick to vertical and overhead surfaces, the ability to produce varied and unusual shapes, and the ability for placement in areas of difficult access all make shotcrete a versatile material for concrete repair.

SHOTCRETE REPAIRS - RECENT EXAMPLES

A good way to appreciate the usefulness of shotcrete in repairing concrete is to review a variety of shotcrete repair projects. The following brief summaries of some projects appearing in the literature in recent years show the versatility of shotcrete for concrete repair.

One of the most unusual uses of shotcrete in recent years was for artistic repairs to the Goetheanum historic auditorium near Basel, Switzerland. [5] The current Goetheanum was begun in 1925 and the concrete shell was completed in 1928, while the main auditorium was not finished until 1957. The building was the first use of reinforced concrete for monumental sculptured forms. It was designed by Austrian social philosopher and spiritual scientist, Rudolf Steiner. The building was intended to create a work of art that included architecture, sculpture, painting, music, speech, and theater, and it was designed to serve the activities of a spiritually striving movement. It still serves this purpose and is the world center of the Anthroposophical Society. It is used for over 130 conferences and meetings each year. In 1989, the need for asbestos removal from the main auditorium ceiling prompted a major rehabilitation of the auditorium. Other objectives included improvement of heating, ventilation, and cooling systems; improvement of lighting, and solving problems of acoustics. The 22,200 cubic yard room that had contained seating for more than 1,000 people needed improved acoustics because the organization's philosophy precluded loudspeaker systems. The repairs had to be solved in an artistic manner consistent with the 1920s design. Wood was considered and rejected after full scale carving samples were made and evaluated. Shotcrete was selected for its ability to form complex shapes covering large areas. The interior of the auditorium was to be surrounded by columns with capitals on top supporting a deep and ornate beam or architrave. The shotcrete would require sculpting to finish the ornamentation on both the beams and columns. Dry-mix shotcrete was used, but with a special mixture to allow the work to be carved and sculpted with hatchets. The mixture included pumice aggregate, expanded clay, white marble sand, white cement, hydraulic lime, and iron oxide for color. Reinforcing rods and expanded metal sheets were used in building formwork, and glass fiber mesh was used in the shotcrete layer for shrinkage strains. An average of 35 artisans worked for about 6 months to sculpt the hardened shotcrete. A total of 4,270 man-hours were used in the actual shotcrete gunning. The final result was an impressive artistic renovation that also solved practical problems. Few crack, and no significant defects or color variations have been found in the work that contains a surface area of 23,400 square feet. The texture and appearance of the surface is very uniform. This project is an excellent example of the unique versatility of shotcrete for repair and rehabilitation of existing concrete structures.

On some repair projects, use of a remote-controlled nozzle can solve difficult application or access problems. Shotcrete Technologies, Inc., reported [6] their involvement in this type of project in repairing a sewer tunnel in Skokie, Illinois. The city of Skokie needed to repair a 75-year-old, 6½-foot-wide, modified-horseshoe shaped tunnel that is 8,800 feet long and about 32 feet below street level. A video camera and flood lights were floated through the two-thirds full tunnel to gather pre-bid information because the tunnel could not be drained at that time for a thorough inspection. Original plans, before the tunnel could be entered, were to reline the tunnel with reinforced concrete, and steel arch forms 200 feet long. When the tunnel was finally drained and mucking operations were underway, some sections of the tunnel were found to be out of line and grade by as much as two feet. Only a short section was straight enough to use the fabricated concrete forms. Concrete placement could be used in the tunnel invert, but reinforced wet-mix shotcrete with a trowel finish was the best solution for the upper part of the tunnel lining. While a hand-held nozzle could have been used, a review of costs on a previous project indicated that a remote-controlled nozzle could cut project costs. Shotcrete Technologies used a robotic arm and nozzle assembly mounted on a wheeled cart to apply shotcrete with accelerator in the small diameter tunnel. The cart was used in a test tunnel to ensure safe operation during actual project work. Electric power was used for all equipment as well as for lights. The operator sat behind the robotic arm and controlled shotcreting operations with a double joystick. The set-accelerating admixture, added at the nozzle, allowed the approximately 6-inch-thick initial shotcrete layer to be placed in one pass. The shotcrete layer was cut to basic shape by hand with a rod. The second, thinner, layer was applied without an accelerator and finished by hand in preparation for an epoxy coating that was to be applied later. The robotic arm allowed accurate and consistent placement in the confined space. Production rates were between 120 and 150 linear feet per day. Compressive strengths at 28 days exceeded 9,000 psi. This project demonstrates not only the versatility of shotcrete as repair material, but also the benefits of specially designed application equipment for use in difficult working spaces.

Shotcrete has also been used for repair and rehabilitation of concrete dams. The entire face of Littlerock Dam in southern California was covered with shotcrete in a seismic retrofit project. [7] This dam was constructed with 28 arches, with each barrel-like arch extending nearly the full height of the dam face. Littlerock Dam has a maximum height of 190 feet and a crest length of 720 feet and was completed in 1924. The dam did not meet current seismic stability criteria because it lacked lateral stability and is located 1.5 miles from the San Andreas fault. Roller compacted concrete was used to construct a gravity section for stability on the downstream side of the dam, and shotcrete containing steel fibers was used to stiffen the upstream arches. Full bond between the shotcrete and the existing concrete arches was required to obtain seismic resistance. Obtaining a minimum tensile bond strength of 150 psi required careful surface preparation. Sandblasting created a roughness profile with a peak-to-valley height of 3/16 inch that exposed, but did not undercut coarse aggregate. Profile gauges were used to document proper preparation. Pre-wetting continuously for at least 24 hours prior to shotcreting was necessary to obtain the required saturated surface dry condition. Cleanliness was confirmed by wiping the prepared surface with a dark cloth to check for dust on the existing concrete. Hardness of the existing surface was considered adequate if it could not be gouged with a knife blade. Anchors and reinforcing steel were also installed on the dam face to further insure integrity of the repair. Wet-mix shotcrete was specified as 6,000 psi at 28 days, containing 100 lb/cy of steel fibers, having a minimum cement content of 675 lb/cy, and containing 10 percent silica fume by weight of cement. Air entrainment was used to obtain 10 to 12 percent air at the shotcrete pump, resulting in about 5 percent air for the in-place shotcrete. Preconstruction testing included measuring surface roughness profiles, tensile bond pull-off tests, visual core grading to evaluate defects, and testing of the shotcrete itself, including compressive strength, absorption, air content, and toughness. Pull-out tests were performed on the anchors. Quality monitoring continued throughout construction. The shotcrete was finished by hand, and water-curing was continuous for a minimum of 7 days. The 48,000-square-foot shotcrete overlay was completed in 90 days. In this project, the shotcrete was required to act as an integral part of the existing dam. Good bond strength was achieved with surface preparation, silica fume, and wet curing. Mechanical connection was provided with anchors and reinforcing bars.

An evaluation of shotcrete repairs on several British Columbia Hydro dams provided recommendations for future shotcrete repairs. [8] Stave Blind Slough Dam, Buntzen Dam, Ruskin Dam, and Jordan Dam were inspected and cores were drilled for laboratory testing. All four dams had been repaired with shotcrete in the past: Stave Dam in 1985, Buntzen Dam in 1965, Ruskin Dam in 1954 and 1973, and Jordan Dam was repaired with shotcrete four times between 1969 and 1990. Both sound and deteriorated shotcrete repairs were found at the dams. Conclusions were that shotcrete was reasonably durable on vertical or inclined surfaces even when it did not meet current standards for air entrainment. On horizontal surfaces, however, non air-entrained shotcrete can suffer severe freezing and thawing damage, even if it contains silica fume and steel fibers. All shotcrete examined had sufficient compressive strength. Even shotcrete with high compressive strength can have a low modulus of elasticity because of the high cement content. Low modulus of elasticity can be an advantage in repairs, as it prevents stress concentrations. Reflection cracking was observed where shotcrete was applied over joints in the substructure. Shotcrete needs contraction joints for crack control just as concrete does. Bond failure was a problem where shotcrete was applied to smooth or poorly prepared concrete. Even sound shotcrete overlays can fail if they trap moisture in the substrate concrete and are not thick enough to prevent freezing in the substrate. Recommendations for future work at these dams included:

- continued use of shotcrete for vertical, inclined, or overhead concrete surfaces on dams

- avoiding trapped moisture behind shotcrete
- sealing cracks against moisture prior to shotcreting
- proper surface preparation, including sufficient roughness profiles, proper moisture condition, and a clean surface
- using a shotcrete mixture appropriate to the specific project
- using a minimum thickness of 3 inches for protected faces, 4 inches on exposed faces, and 10 inches where frost action could damage saturated substrate concrete
- using the natural gunned surface without further finishing where possible
- using moist curing

While these findings are for specific dams in a specific climate, they are important for other projects as well.

Shotcrete has also been used to repair prestressed concrete tanks that were originally built using dry-mix shotcrete.[9] The authors of the referenced article have engineered the repairs of more than 30 prestressed tanks to prevent further, accelerated deterioration. Predicted additional service life after repairs is 20 years or more with proper maintenance. The dome, forming the top of the tank, usually shows the greatest deterioration on tanks built over 30 years ago. Placing shotcrete on a horizontal plane is more likely to produce rebound inclusions and horizontal spaces between shotcrete layers that can fill with water and cause failure upon freezing. This was especially true 30 years ago, when over-sanded mixes were commonly used. The dry-mix shotcrete itself can be very durable in freezing and thawing environments if it does not contain laminations. Some prestressed tanks constructed over 40 years ago are still in excellent condition. Delaminated areas of the dome are outlined with a saw cut to prevent feather edges. The area is then chipped to sound material and repaired with shotcrete and no bonding agent. If the damage is through the total thickness of the dome, a wood form is constructed underneath. When the damaged area exceeds about 30 to 50 percent of the surface area, a full dome overlay should be considered. The dome ring is a prestressed ring at the top of the circular tank that is designed to withstand the thrust load of the dome weight and any additional snow loading. Deterioration of the dome ring can lead to exposed prestressing strands and corrosion. After removing deteriorated shotcrete from original construction, the prestressing wires can be cleaned by sandblasting and evaluated for damage. Minor wire damage can be supplemented by including reinforcement bars in the repair. Severe damage to prestressing wires requires that supplemental prestressing wires be installed before shotcrete repairs begin. Tank wall repairs are required less frequently than dome repairs. Tank wall repairs usually involve delamination of the shotcrete covering the wires. An engineering evaluation is made to evaluate any loss due to corrosion of wires, and repairs are made as described above for the dome ring. A follow-up inspection and maintenance recommendations are made within 2 years of shotcrete repairs. Shotcrete repairs can be cost effective in extending the useful life of the tank.

Shotcrete is frequently used to repair concrete bridges. In a recent article [10], Steve Gebler described the technology involved. Bridges are especially susceptible to freezing and thawing damage, chloride induced corrosion, overloading, and alkali-silica reaction damage. As with any concrete repair, it is important to determine the cause and extent of damage and to take action to eliminate or reduce the cause. With bridges, this might involve petrographic examination, determining chloride-ion content, and improving drainage. Deteriorated concrete must be removed and corrosion-damaged steel should be cleaned using dry sandblasting and then repaired. The outer edges of the repair should be sawcut, and sufficient space (at least 3/4 inch) is needed behind rebars to allow shotcrete placement. The repair opening should be shaped to prevent rebound inclusion. Concrete with high porosity should be kept moist for at least 24 hours before shotcrete application, while denser concrete can be kept moist for at least 1 hour. Bridge repairs of low volume are usually made with the dry-mix process, while larger jobs use either dry-mix or wet-mix shotcrete. Silica fume is frequently used, and for wet-mix shotcrete, silica fume is used with a superplasticizer. Mr. Gebler recommends air entrainment for wet-mix shotcrete, but states that dry-mix does not need purposely entrained air to develop freezing and thawing damage resistance. While the shotcrete mixture can be designed with most materials available for concrete, Mr. Gebler does not recommend set accelerators for bridge repairs, as they can decrease strength and increase freezing and thawing deterioration problems. When possible, bridge repairs should be applied in a single full-thickness layer to avoid delaminations. A blowpipe should be used for rebound removal. The shotcrete repair should completely encapsulate the bridge element being repaired and have at least a 3 percent slope for drainage. Partial encapsulation might allow water to enter and be trapped by the new dense shotcrete repair. This could cause damage on freezing and could also allow more salts to reach the reinforcing. Because taking a bridge out of service is inconvenient to the public, repairs must be done right the first time. Preconstruction panels to qualify the crew, equipment, and shotcrete mixture need to be fabricated. Rebar encasement, shotcrete density, shotcrete uniformity, and shotcrete strength can be evaluated on the test panels. Specialized tests such as tensile bond are sometimes specified. Requirements for aesthetics are sometimes necessary in bridge repairs, but can be expensive and can be eliminated where repairs will not be visible to the public.

The examples above are just a small sampling of articles on shotcrete for concrete repair that were published in the last 10 years. While they are sufficient to demonstrate the versatility of shotcrete, it would be useful to know other recent shotcrete uses for concrete repair. Without going into details, the following list gives some other applications seen in the literature since 1990.

- Storm and sanitary sewer rehabilitation
- Subway tunnel rehabilitation
- Multistory parking structure repairs
- Grain silo repairs
- Water treatment plant resurfacing
- Shipyard dry dock rehabilitation
- Historic railroad roundhouse repairs
- Adapting old buildings to new uses
- Restoration of boat docks
- Articles giving research results on shotcrete and shotcrete materials
- Articles on shotcrete for new construction

CONCLUSIONS

Shotcrete technology has advanced impressively over the past 90 years. This is a result of innovations not only in shotcrete application equipment and methods, but also advances in concrete technology. Articles appearing in the last decade on the use of shotcrete for concrete repair document current technology and the versatility of shotcrete for this purpose. Reclamation can continue to successfully use shotcrete as one of its methods of concrete repair if current technology is understood and shotcrete is used within its limitations.

BIBLIOGRAPHY

[1] American Concrete Institute, *Cement and Concrete Terminology*, Publication SP-19(90), ACI 116R-90, Detroit, Michigan, 1990.

[2] Wolsiefer, John Sr., and Dudley R. Morgan, "Silica Fume in Shotcrete," *Concrete International*, American Concrete Institute, Detroit, Michigan, April, 1993.

[3] Warner, James, "Shotcrete for Repair and Rehabilitation," *Concrete Repair Bulletin*, May/June 1997 issue, International Concrete Repair Institute, Sterling, Virginia.

[4] Warner, James, "Understanding Shotcrete–Structural Applications," *Concrete International*, American Concrete Institute, Detroit, Michigan, October 1995.

[5] Hasler, Hans; Pietro Teichert, and D.R. Morgan, "Artistic Shotcrete for a Historic Auditorium," *Concrete International*, American Concrete Institute, Farmington Hills, Michigan, March 1999.

[6] Shotcrete Technologies, Inc., *Skokie, Illinois Sewer Tunnel Project Report*, Idaho Springs, Colorado, June 1999.

[7] Forrest, M.P.; D.R. Morgan, J.R. Obermeyer, P.L. Parker, and D.D. LaMoreaux, "Seismic Retrofit of Littlerock Dam," *Concrete International*, American Concrete Institute, Detroit, Michigan, November 1995.

[8] Heere, Roland; Dudley Morgan, Nemkumar Banthia, and Yoga Yogendran, "Evaluation of Shotcrete Repaired Dams in British Columbia," *Concrete International*, American Concrete Institute, Detroit, Michigan, March 1996.

[9] Poston, Randall W., Daniel J. McCarthy, and Morris Schupack, "Repair of Wire-Wound Prestressed Concrete Tanks," *Concrete International*, American Concrete Institute, Detroit, Michigan, March 1992.

[10] Gebler, Steve, "Repair of Bridge Elements Using Shotcrete," *Shotcrete Magazine*, American Shotcrete Association, Sterling, Virginia, May 1999.